

# A stellar endgame – the born-again Sakurai’s object

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**Abstract.** The surface chemical composition of this remarkable star shows that it is hydrogen-deficient, carbon-rich and enriched in the light *s*-process elements. Spectra taken in May and October 1996 indicate a decrease in the surface hydrogen abundance by 0.7 dex in five months along with an increase in the abundances of Li, Sr, Y and Zr. The abundance changes are in agreement with the hypothesis of the star being a rapidly evolving “born-again” AGB star experiencing a final He-shell flash, similar to FG Sge. The <sup>12</sup>C/<sup>13</sup>C ratio in October is very low, also suggesting hydrogen ingestion. By chemical composition, Sakurai’s object resembles the R Coronae Borealis (R CrB) stars.

**Key words:** Stars: individual: Sakurai’s object – Stars: evolution – Stars: AGB and post-AGB – Stars: abundances – Stars: variables: other – Stars: individual: FG Sge

## 1. Introduction

The nova-like brightening of Sakurai’s object in Sagittarius has been attributed to the final helium-shell flash of a central star of a planetary nebula, that returns the star towards the domain of red giants in the Hertzsprung-Russell diagram (Duerbeck & Benetti 1996). Few stars have been identified with this phase of evolution: examples include FG Sge, V605 Aql, the planetary nebulae Abell 30, Abell 78 and N66. It is expected that a born-again red giant will consume hydrogen and become starkly hydrogen-deficient, helium- and carbon-rich. Low-resolution spectra led Duerbeck and Benetti (1996) to suggest that Sakurai’s object is hydrogen-poor. The presence of strong lines of neutral carbon and oxygen was also noted.

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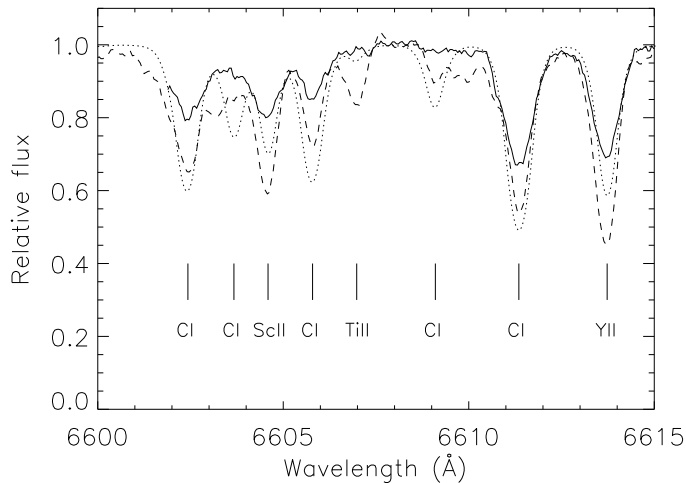
Changes of the surface chemical composition may be rapid for born-again AGB stars, as was observed for FG Sge. Sakurai’s object offers the prospect of monitoring such secular changes in another born-again candidate. Observations, as reported here, are surely crucial for an improved understanding of the final He-shell flash.

## 2. Observations

Spectra covering 3700-10150 Å at a resolution of about 30,000 were obtained with the 2.7 m telescope at McDonald Observatory on May 5 and 6 and on October 7, 1996. A spectrum was also obtained with the 2.1 m telescope: this spectrum from May 9, 1996, covers the region 5720 Å to 7200 Å at a resolution of about 60,000.

## 3. Chemical composition

Our analysis is based on line-blanketed, hydrogen-deficient model atmospheres, similar to those described by Asplund et al. (1997) but with a range of hydrogen abundances. In estimating the stellar parameters  $T_{\text{eff}}$ ,  $\log g$  and hydrogen abundance various ionization (Fe I/Fe II, Mg I/Mg II, Si I/Si II, Cr I/Cr II) and excitation equilibria ([O I]/O I, Fe I, Fe II) together with the H $\beta$  and H $\alpha$  line profiles (with line broadening data following Seaton 1990) have been used. The C/He ratio was determined from the C II and He I lines in the May spectra, which indicate C/He  $\simeq$  10 %. The same ratio had to be assumed for October when the lines were too weak to be utilized. The microturbulence parameter was estimated from Ti II, Fe I and Fe II lines of different strengths. The May spectra are characterized by  $T_{\text{eff}} = 7500 \pm 300$  K,  $\log g = 0.0 \pm 0.3$ , and  $\xi_t = 8.0 \pm 1.0$  km s<sup>-1</sup>, while it had cooled significantly in October:  $T_{\text{eff}} = 6900$  K,  $\log g = 0.5$ , and  $\xi_t = 6.5$  km s<sup>-1</sup>. In fact, the derived parameters are not consistent with a constant stellar luminosity but rather indicate a decrease by a factor of 4, which is not supported by the observed

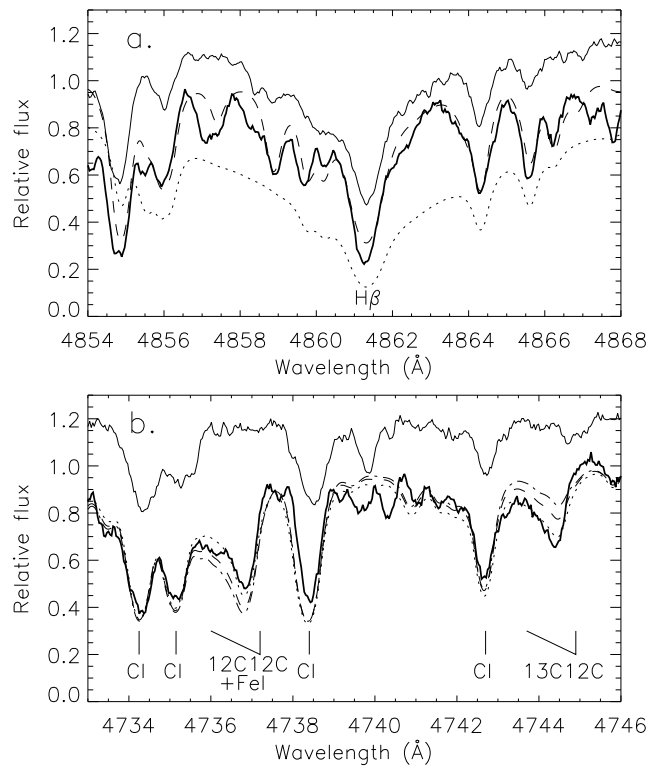


**Fig. 1.** A selected piece of spectrum in May (solid) and October (dashed) showing the increase of some elements, e.g. Sc, Ti, and Y. The dotted curve is the synthetic spectrum with the stellar parameters of October but with the May abundances. Note also that all predicted C I lines are too strong

photometry. It could, however, be that hydrostatic equilibrium is inapplicable in May due to an expansion of the star or effects of turbulent pressure: a dynamical atmosphere can be mimicked by an underestimate of  $\log g$  when assuming hydrostatic equilibrium. Indeed, with the May parameters the star is located at the classical Eddington limit (e.g. Asplund & Gustafsson 1996).

The analysis of the C I lines reveals the same inconsistency between theoretical and observed line strengths as for R CrB stars (Gustafsson & Asplund 1996; Lambert et al., in preparation): the strengths of weak lines predicted with the input C abundance are a factor of 4 stronger than observed (Fig. 1 and 2). It should be noted that no agreement between all  $T_{\text{eff}}\text{-}\log g$  indicators could be achieved using consistent C abundance for the analysis. Naturally, this C I problem makes the absolute abundances uncertain but relative abundances are generally expected to be much less affected (Lambert et al., in preparation).

The derived LTE abundances for May and October are summarized in Table 1. More details on the analysis and atomic data (lines, gf, hfs, etc) as well as a comparison with V854 Cen will be given elsewhere. The weak Balmer lines certainly rule out a solar hydrogen abundance (Fig. 2). Note that the absolute abundances of most elements are effectively unchanged from May to October within the uncertainties (typically  $\leq 0.3$  dex). Some elements, however, exhibit a marked change, for example, hydrogen declined as lithium and the light *s*-process elements increased in abundance by a factor of about 4 (Fig. 1). Also Sc, Ti, Cr and Zn seem to have increased during the time-span (Fig. 1). The general agreement between the May and October abundances for most elements suggests that the stellar parameters are not seriously in error, which could otherwise have resulted in spurious abundance ef-



**Fig. 2.** **a** H $\beta$  in October (thick solid) compared with predicted line profiles for solar H (dotted) and H-deficient by 3.0 dex (dashed). **b** C<sub>2</sub> (1-0) Swan band for  $^{12}\text{C}/^{13}\text{C} = 2$  (dotted), 5 (dashed) and 10 (dash-dotted), together with the observed October spectrum (thick solid). Also shown in both figures are the May spectra (solid) but displaced upwards by 0.2 for clarity

fects. Besides Li, the abundances of elements showing variations are not very sensitive to the stellar parameters: the required  $\Delta T_{\text{eff}} \approx 1000$  K for either May or October to annul the abundance variations would be inconsistent with the  $T_{\text{eff}}\text{-}\log g$  indicators and introduce other as severe changes (e.g. for Ca) less easily explainable; a different  $\log g$  can not simultaneously explain all changes. It would also only aggravate the luminosity discrepancy. Hence, the few changes seem to be real. Furthermore, they are limited to elements expected to show alterations due to a final flash.

The metallicity of Sakurai’s object is, judging from Fe, slightly below solar by 0.2 dex in mass fraction (0.9 dex if the input rather than the spectroscopic C abundance is adopted). The quantities [Si/Fe], [S/Fe], [Ca/Fe], and [Ti/Fe], which are 0.8, 0.6, 0.3 and 0.4 respectively, are, if unchanged from the star’s birth, also indicative of a metal-poor star (Edvardsson et al. 1993). An isotopic ratio  $1.5 \leq ^{12}\text{C}/^{13}\text{C} \leq 5$  is determined from the strong C<sub>2</sub> (1-0) and (0-1) Swan bands (Fig. 2). The strengthening of the C<sub>2</sub> bands due to the change in stellar parameters is clearly illustrated in Fig. 2.

It is of considerable interest to compare the compositions of Sakurai’s object and FG Sge, another born-again

**Table 1.** Chemical compositions of Sakurai’s object, the R CrB stars and the Sun (normalized to  $\log(\Sigma\mu_i\epsilon_i) = 12.15$ )

Element	Sun <sup>a</sup>	Sakurai’s object		R CrB <sup>b</sup>	
		May	October	majority	minority
H	12.0	9.7	9.0		< 4.1 – 10.8
He	11.0	11.4 <sup>c</sup>	11.4 <sup>c</sup>	11.5 <sup>c</sup>	11.5 <sup>c</sup>
Li	3.3 <sup>a</sup>	3.6	4.2		
C	8.6	9.7 <sup>d</sup>	9.8 <sup>d</sup>	8.9 <sup>d</sup>	8.6 – 9.5 <sup>d</sup>
N	8.0	8.9	8.9	8.6	7.6 – 8.6
O	8.9	9.5	9.4	8.2	7.5 – 8.8
Ne	8.1	9.3			7.9 – 9.6
Na	6.3	6.7	6.8	6.1	5.8 – 5.9
Mg	7.6	6.6	6.5		6.1 – 7.3
Al	6.5	6.6	6.3	6.0	5.3 – 5.6
Si	7.5	7.1	7.5	7.1	7.3 – 8.1
S	7.3	6.6	6.9	6.9	6.7 – 7.6
K	5.1	4.8	5.0		
Ca	6.4	5.6	5.5	5.4	5.0 – 5.3
Sc	3.2	3.1	3.9		
Ti	5.0	4.1	4.6		
Cr	5.7	4.5	5.1		
Fe	7.5	6.3	6.6	6.5	5.0 – 5.8
Ni	6.2	6.1	6.2	5.9	5.2 – 5.8
Cu	4.2	4.9	5.0		
Zn	4.6	4.7	5.4	4.3	3.8 – 4.1
Rb	2.6	< 3.7	4.6		
Sr	3.0	4.9	5.4:		
Y	2.2	3.3	4.2	2.1	0.6 – 2.8
Zr	2.6	3.0	3.5		
Ba	2.1	1.5	1.9	1.6	0.7 – 1.3
La	1.2	< 1.6	1.5		

<sup>a</sup> From Grevesse et al. (1996). For Li the meteoritic value is adopted.

<sup>b</sup> From Rao & Lambert (1996) and Jeffery & Heber (1993). The majority is an average of 14 stars while the minority consists of V CrA, VZ Sgr, V3795 Sgr and DY Cen.

<sup>c</sup> Input C/He ratio for model atmospheres: C/He=1% assumed for R CrB stars and 10% estimated for Sakurai’s object from the 1996 May spectra.

<sup>d</sup> Spectroscopically determined C I abundance, see text.

candidate which has recently experienced R CrB-like visual declines. FG Sge resembles Sakurai’s object in that it is strongly *s*-element enriched (Langer et al. 1974), as well as carbon-rich and poor in iron-group elements, except for Sc (Kipper & Kipper 1993). In FG Sge, however, the heavy *s*-elements are as overabundant as the light, and it has not yet been shown to be hydrogen-deficient. FG Sge may therefore have experienced a late shell flash as a luminous post-AGB star rather than a final flash as a white dwarf (Blöcker & Schönberner 1996).

Two of the outstanding aspects of the chemical composition of Sakurai’s object are hallmarks of the R CrBs: H-deficiency and a high C content, but also other similarities in relative abundances exist (Lambert et al., in preparation; Rao & Lambert 1996; Lambert & Rao 1994).

Except for the high Y/Fe other observed X/Fe ratios are similar to those found in R CrB stars. In particular it resembles the (relatively) H-rich V854 Cen (Asplund et al., in preparation). If, however, C/He is correctly estimated, it may sooner be related to objects such as V605 Aql, Abell 30 and 78 and the hot R CrB star V348 Sgr, which are also surrounded by planetary nebulae and have been proposed to be final flash candidates (Renzini 1990).

Similar abundance patterns as presented here for Sakurai’s object have also been obtained in less detailed analyses by Shetrone & Keane (1997) and Kipper & Klochkova (1997). Shetrone & Keane’s finding of a near normal H abundance is however very puzzling.

#### 4. Abundance variations and nucleosynthesis

In broad terms, the composition of Sakurai’s object shows evidence of severe contamination by material exposed to hydrogen and helium burning and associated nuclear reactions. Close examination provides some interesting constraints on the nucleosynthesis experienced by the star.

The present atmosphere is not a simple mix of initial unprocessed gas, gas run through the H-burning CNO-cycles, and H-exhausted gas exposed to He-burning, but must have been accompanied by further processing. This is demonstrated by the low observed  $^{12}\text{C}/^{13}\text{C}$  ratio, which encompasses the equilibrium value of 3.5 for CNO-cycling. As the equilibrium abundance of  $^{13}\text{C}$  is very low following He-burning, the observed ratio suggests that  $^{12}\text{C}$  from He-burning has been exposed to hot protons. It would seem that C-rich material from He-burning has been mixed with ingested hydrogen such that the proton supply is effectively exhausted in converting inhibited (see Renzini 1990).

Not all protons are consumed in He-rich regions. Production of lithium is ascribable to the Cameron-Fowler (1971) mechanism. Here  $^3\text{He}$  synthesised in a low mass main sequence star is converted to  $^7\text{Li}$  in an envelope that convects  $^7\text{Li}$  to low temperatures where it survives until re-exposed to high temperatures. Production of lithium implies H-burning in regions not previously exposed to H-burning temperatures;  $^3\text{He}$  which is destroyed in regions that have undergone H-shell or H-core burning can hardly be resynthesised. The observed Li is not a fossil from an earlier stage as a Li-rich AGB star: the predicted Li/H ratio for AGB stars which have undergone hot-bottom burning is  $10^{-8}$  while the observed ratio is  $10^{-5}$  to  $10^{-6}$  and hydrogen consumption necessarily destroys fossil lithium. The overabundant Na and Al have likely been synthesised through  $^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$  and  $^{25}\text{Mg}(p,\gamma)^{26}\text{Al}$ . As in other H-deficient stars Ne is very high, which can not be explained by  $\alpha$ -captures on N from initial CNO, but must be due to products of He-burning and possibly additional CNO-cycling.

A remarkable feature of Sakurai’s object is the large overabundance of light *s*-process elements and the high

ratio of light to heavy *s*-process elements. Probably,  $^{13}\text{C}(\alpha, n)^{16}\text{O}$  is the neutron source. The *s*-processing may be characterized by the neutron exposure  $\tau$ . We find a good fit to the abundances from Ni to La for October with  $\tau = 0.2 \pm 0.1 \text{ mb}^{-1}$  using Malaney’s (1987) predictions for a single exposure. The Rb abundance indicates a low neutron density of  $N_n \approx 10^8 \text{ cm}^{-3}$  (Malaney 1987), while no useful limit could be set on the Tc abundance. An exponential distribution of exposures provides less good agreement with the observed abundances. For the R CrB star U Aqr, which also shows light *s*-element enhancements, Bond et al. (1979) obtained  $\tau \simeq 0.6 \text{ mb}^{-1}$ . Such exposures imply that about 10 neutrons were captured by each Fe seed nucleus. Given that the observed ratio  $^{13}\text{C}/\text{Fe} \simeq 10^3$ , the exposure, even in the presence of neutron poisons such as  $^{14}\text{N}$ , seems an achievable goal. The fact that Ni, Cu and Zn are well fit by the predictions indicates that the envelope consists mostly of material exposed to neutrons. This fact also likely explains the anomalous high ratios of K/Fe and Sc/Fe.

The final He-shell flash may occur in a luminous post-AGB star or the white dwarf that evolves from the post-AGB star. In the latter case, hydrogen may be mixed with deep layers of He and C and consumed. In contrast, the H-burning layer in the post-AGB star prevents deep mixing. About 10% of all AGB stars may experience their final He-shell flash as a white dwarf and, if H consumption is severe, may convert the born-again AGB star to an R CrB star (Renzini 1990; Iben et al. 1996). Iben & MacDonald (1995) have presented a model in which mixing and nucleosynthesis were followed: their chosen model of a  $0.6 M_{\odot}$  star ended with an outer layer having the abundance ratios (by number of atoms)  $\text{H}/\text{He} \simeq 10^{-0.8}$ ,  $\text{C}/\text{He} \simeq 10^{-1.2}$ ,  $\text{N}/\text{C} \simeq 10^{-0.5}$ , and  $\text{O}/\text{C} \simeq 10^{-1.3}$ . This resembles the composition of Sakurai’s object, apart from the predicted H deficiency not being as severe as observed. The model O/C ratio is lower than observed but might be raised by adjustment of the uncertain rate for the reaction  $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ . In summary, final flash models offer a tantalising prospect of accounting for the observed composition of Sakurai’s object.

Life as a born-again AGB star is brief: the model by Iben & MacDonald (1995) brightens by a factor of 10 and cools from  $T_{\text{eff}}$  of 40,000K to 6300K in just 17 yr. Evolution over the narrow temperature range covered by Sakurai’s object between May and October is, of course, much faster. The evolutionary timescale seems similar to that of V605 Aql (Lundmark 1921). The timescale for compositional changes for Sakurai’s object is likely even shorter; processed material rising from below will mix very quickly with the atmosphere. The other final flash candidate FG Sge has also showed rapid abundance alterations, e.g. some *s*-process elements increased by 0.8 dex in 7 years (Langer et al. 1974).

It is now important to extend the few available calculations of the final flash to a wider range of initial conditions,

and to include Li-production and *s*-processing. The hints that the surface composition is evolving rapidly must be pursued by continued spectroscopic observations, which may shed further light on its evolutionary status and relation to the R CrB stars; we may have witnessed the birth of an R CrB star. Furthermore, a determination of the nebular composition would reveal the original composition of Sakurai’s object prior to the final flash. Monitoring the visual variability of the star searching for R CrB-like declines is naturally of importance.

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